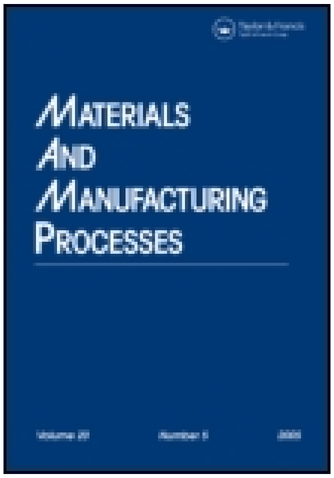

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Machining of AISI 316 Stainless Steel under Carbon-Di-Oxide Cooling

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Machining of AISI 316 Stainless Steel under Carbon-Di-Oxide Cooling

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This work investigates the effect of carbon dioxide (CO_2) as the cutting fluid in turning AISI 316 stainless steel work material on cutting temperature, cutting force, tool wear, surface roughness, and chip morphology when compared to dry and wet machining. Compared to wet machining, in CO_2 machining the cutting temperature was reduced up to 35%, and the surface finish of the machined workpiece increased by 4–52% along with the reduced tool wear.

Keywords Chips; CO_2 machining; Cutting temperature; Turning; Wear.

Introduction

High cutting temperature in the cutting zone always associates with the rapid tool failure, poor surface finish, and less dimensional accuracy [1]. Conventionally applied coolants fail to provide desirable control of cutting temperature, as they cannot penetrate into the chip-tool interface predominantly due to plastic contact between the tool and chip, especially at high cutting speeds [2, 3]. Further, the application of conventional fluids has also posed environmental and disposal problems. Earlier, various machining investigations and cooling techniques have been carried out extensively using liquid nitrogen (LN2) as the coolant to reduce the cutting temperature, improve the surface finish, and reduce the tool wear [4–13]. The major disadvantage of using LN2 as the coolant is increased overall machining cost [6] and also that its extreme low temperature (−196°C) pre-cools the workpiece, which increases the cutting forces and abrasion to the tool [7]. Hence, in the present work, a high pressure jet of CO_2 (−78°C) is used as an efficient cutting fluid and coolant for machining purpose.

Literature review

Research has already been undertaken in the area of cryogenic machining to explore the benefits of using cryogenic coolants and to evaluate its economic feasibility. Many researchers have used LN2 as the prime cryogenic coolant; hardly any have used CO_2 for machining purpose. The application of LN2 also reduced the cutting forces and tool wear with better surface finish in many machining processes [6, 8]. Hong et al. [7, 9] reported that a minimum quantity of LN2 applied on to the chip tool interface is superior to emulsion cutting, in lowering the cutting temperature. Dhar and Kamruzzaman [10] have also studied the effect of LN2 coolant on cutting temperature, tool wear, surface finish, and the dimensional deviation in turning of AISI 4037 steel. Dhananchezian and Kumar [11, 13] used a modified cutting insert to supply LN2 and proved that there was a drastic reduction in the cutting temperature with subsequent reduction in the tool wear, reduced cutting forces, and improved surface finish. It was also reported that the use of LN2 as the cryogenic coolant increased the coolant consumption rate, which increased the overall machining cost [6]. The nonfeasibility and disadvantages of using LN2 as the cryogenic coolant lead the researchers to use CO_2 and other gases as the cutting fluid. De Chiffre et al. [14] proved that the cryogenic CO_2 was a better coolant with respect to tool life, cutting forces, chip disposal, and surface finish in Parting/Grooving and threading operations. Application of carbon-di-oxide also proved to be the better cutting fluid on producing lower cutting forces and better surface roughness [15]. The effect of water vapor, oxygen, and CO_2 gases as coolant was also studied by Liu et al. [16, 17]. It was found that the tool life was improved to a greater extent on reduction of the tool wear with the application of such coolants. The main objective of the current work is to study the effects of CO_2 as the cutting fluid in machining AISI 316 stainless steel and to compare the cutting temperature, cutting forces, tool wear, surface roughness, and chip morphology with wet and dry machining.

Experimental setup and procedure

The experimental conditions are given in Table 1. The CO_2 gas is supplied from the cylinder through a nozzle whose outlet tip is Ø 2 mm. The nozzle is fixed at a distance of 50 mm from the cutting zone. A CO_2 regulator and flow meter is also attached for maintaining the pressure and flow rate of the gas. In wet machining, an

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TABLE 1.—Experimental conditions.

Machine tool	High power rigid lathe (Nagmati-175)
Work specimen	AISI 316 stainless steel (Ø 60 mm × 300 mm)
Cutting insert	PVD coated carbide insert (CNMG 120404 MP 431 KC 5010)
Rake angle	−5°
Clearance angle	5°
Machining parameters	
Cutting velocity	41, 94, and 145 m/min
Feed rate	0.051, 0.096, 0.143, and 0.191 mm/rev
Depth of cut	1 mm
Machining environments	Dry, wet, and CO_2
CO_2 flow rate	3 g/s

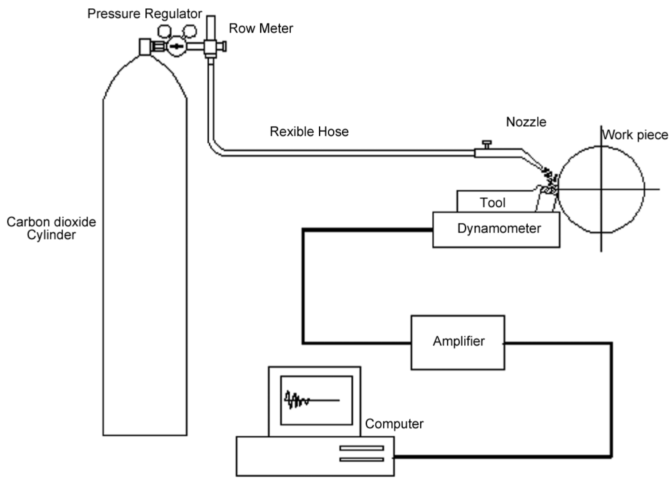


FIGURE 1.—Experimental setup for CO_2 machining.

oil-based conventional coolant is supplied by the same nozzle which is used for the CO_2 supply. The cutting temperature was measured by a calibrated noncontact type infrared (IR) thermometer which can measure a temperature range of −50°C to 1,000°C. Cutting forces were measured using a three-component Kistler piezoelectric dynamometer and a multichannel charge amplifier. The cutting inserts were examined for tool wear under a scanning electron microscope (SEM). The average surface roughness value *Ra* for the finished part along the job axis is found by using a talysurf surface roughness tester. The experimental setup for CO_2 machining is shown in Fig. 1.

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of CO_2 Cooling on Cutting Temperature

Figure 2 shows the variation of cutting temperature under dry, wet, and CO_2 machining conditions.

It was found that the cutting temperature increased with the increase in cutting velocity and feed rate. In general, the cutting fluids mainly depend on heat convection to reduce the cutting temperature in machining. CO_2 in gas form has the capability to reduce the contact friction of tool-chip interface with high efficiency of lubricating action and better penetration. Application

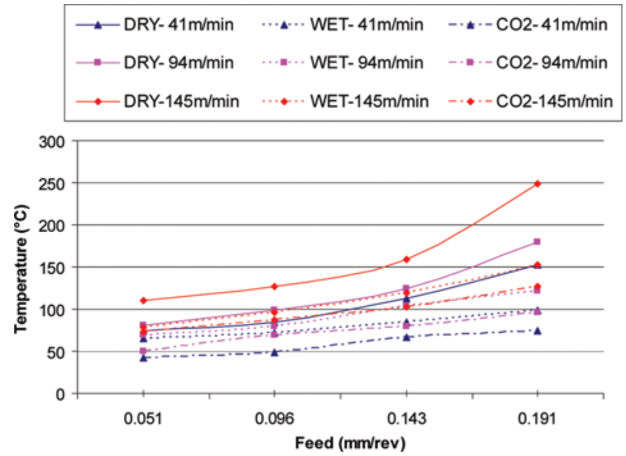


FIGURE 2.—Variation of cutting temperature in different machining environments (color figure available online).

of CO_2 gas reduced the cutting temperature more than the dry and wet machining. The measured cutting temperature at a cutting velocity of 41 m/min and the feed rate of 0.191 mm/rev were found to be 152°C and 75°C for dry and CO_2 machining, respectively. It was observed that in CO_2 machining the cutting temperature reduced up to 50% over the dry machining. The cutting temperature at a cutting velocity of 41 m/min and the feed rate of 0.051 mm/rev were 65.1°C and 42.4°C for wet and CO_2 machining, respectively. It was observed that in CO_2 machining, the cutting temperature reduced up to 35% over the wet machining. The deviations of cutting temperature under CO_2 machining environment with respect to dry machining and wet machining were in the range 29–50% and 7–35%.

Variation of Main Cutting Force in Different Machining Environments

The main cutting forces of dry, wet, and CO_2 machining are illustrated in Fig. 3.

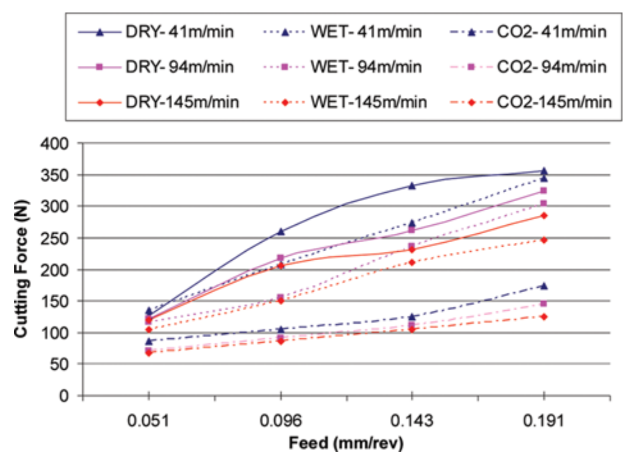
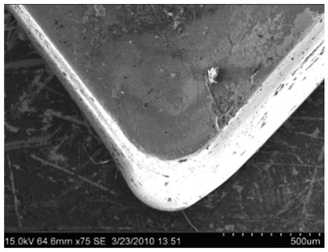
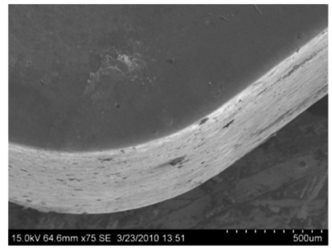
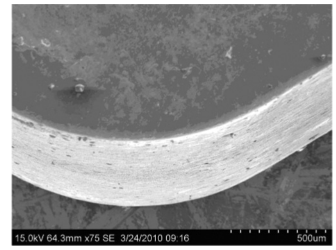
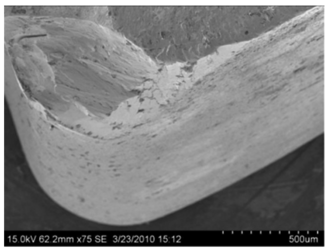
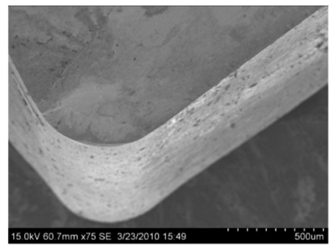
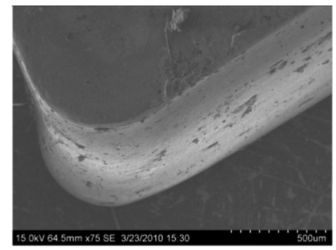
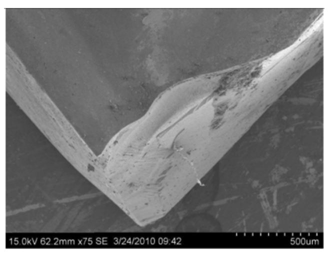
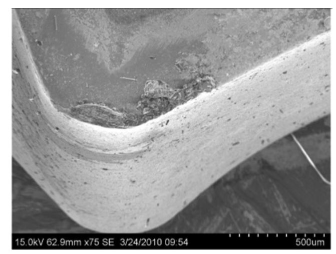


FIGURE 3.—Comparison of cutting force with feed rate (color figure available online).

TABLE 2.—SEM images of the used cutting inserts.

Cutting velocity (m/min)	Dry	Wet	CO_2
41			
94			
145			

It was observed that the cutting force decreased with increase in the cutting velocity. This is because when the cutting velocity increases, the cutting temperature also increases, as a result softening of the material takes place, hence requiring lesser amount of cutting force to shear the workpiece. Moreover, when the CO_2 coolant was applied, the cutting forces were reduced considerably as the high speed jet filled up the capillaries of tool-chip effectively forming the boundary layer reducing the friction and the stickiness of the tool rake with the chips produced. The application of CO_2 coolant reduced the cutting forces to an extent of about 35 to 55% when compared to wet machining. It was also observed that when the feed rate was increased, the cutting forces also increased due to the increase in the chip load.

Tool Wear Analysis

The tool wear mechanism was studied by machining the workpiece at different cutting velocities with constant feed rate of 0.191 mm/rev for all machining environments. Table 2 shows the SEM images of the cutting inserts used for machining after 5 min duration.

Comparing the images in Table 2, it can be noticed that the inserts used for CO_2 machining have lesser crater and flank wear than those of dry and wet machining.

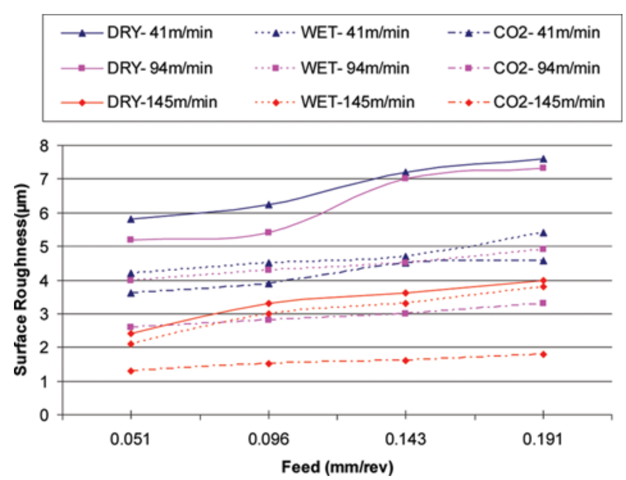


FIGURE 4.—Comparison of surface roughness with feed rate at different machining environments (color figure available online).

TABLE 3.—Images of chips obtained in different machining environments.

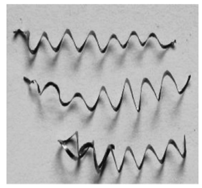
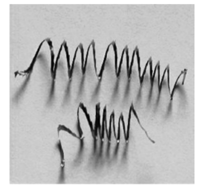
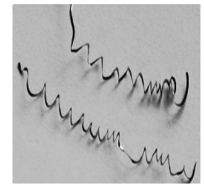
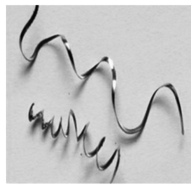
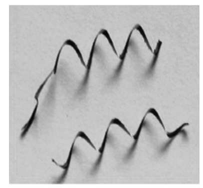
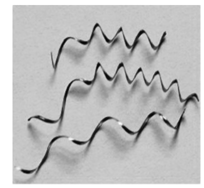
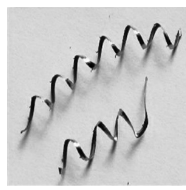
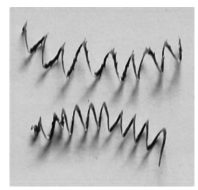
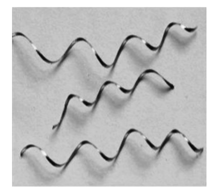
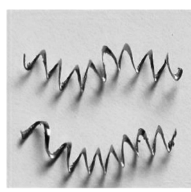
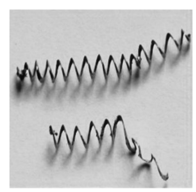
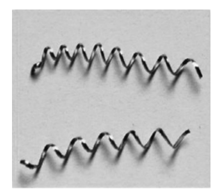
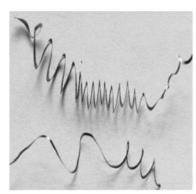
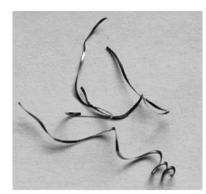
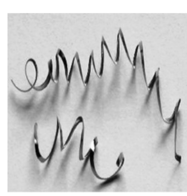
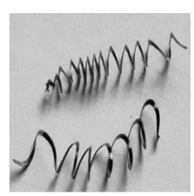
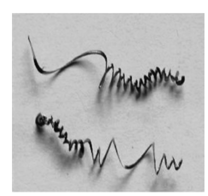
Cutting velocity (m/min)	Feed (mm/rev)	Dry	Wet	CO_2
41	0.051			
	0.096			
	0.143			
	0.191			
94	0.051			
	0.096			

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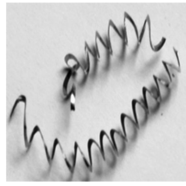
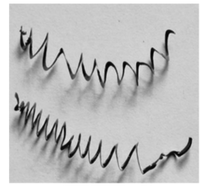
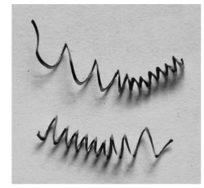
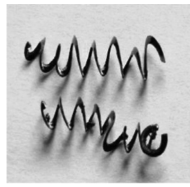
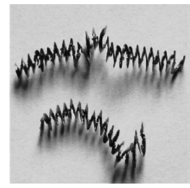
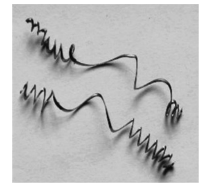
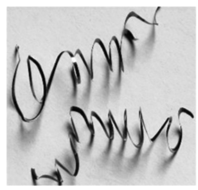
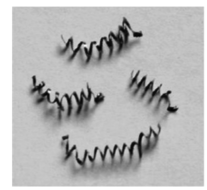
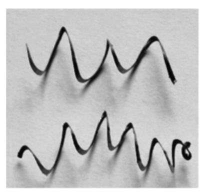
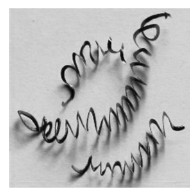
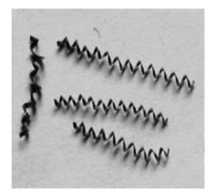
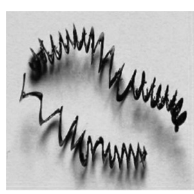
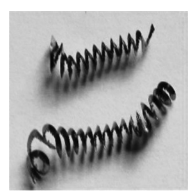
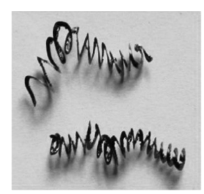
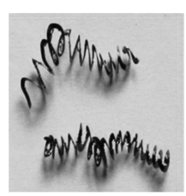
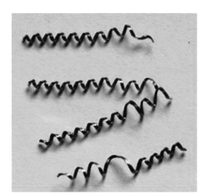
TABLE .—Continued

Cutting velocity (m/min)	Feed (mm/rev)	Dry	Wet	CO_2
	0.143			
	0.191			
145	0.051			
	0.096			
	0.143			
	0.191			

The friction status in the tool-chip interface and the cutting forces reduced better on the application of CO_2 that resulted in the reduced flank wear. At low cutting velocity (41 m/min) in dry and wet machining, deep scratches were found in the flank region, which was smaller and negligible in the case of CO_2 machining. Microchipping and plastic deformation were observed on the rake face in dry and wet machining. Severe amounts of groove wear and notch wear were also observed on the cutting edge in dry and wet machining. The cutting edge was damaged severely at high cutting velocities (94 m/min and 145 m/min) and produced poor surface finish. In wet machining, when the cutting velocity was 94 m/min, the tool had the growing crater, and the tool coating was almost worn out on the rake face in addition to the excess of flank wear. Deep craters and flaking was also observed during wet machining at high cutting velocity of 145 m/min. In CO_2 machining, even at high cutting velocity of 145 m/min, the amount of crater observed was less along with the lesser flank wear. At higher cutting velocities, the diffusion of work material on the tool insert was observed due to the higher cutting temperatures in all the machining environments.

Effect of CO_2 Cooling on Surface Roughness

Figure 4 shows the variation of surface roughness values with different cutting velocities and feed rates.

The surface roughness of the machined part increased with the increase in the feed rate. It was also noticed that as the cutting velocity increased the surface finish obtained was better. The reduction in cutting force and the friction status in the tool-chip interface lowered the cutting temperature that resulted in good surface finish. The measured surface roughness values at a cutting velocity of 94 m/min and the feed rate of 0.143 mm/rev was 7 μm and 3 μm for dry and CO_2 machining, respectively. It was observed that in CO_2 machining, the surface finish gets better by 57% over dry machining. Similarly, the surface roughness values at a cutting velocity of 145 m/min and the feed rate of 0.191 mm/rev was 3.8 μm and 1.8 μm for wet and CO_2 machining, respectively. It was observed that in CO_2 machining, the surface finish got better by 52% over the wet machining. In CO_2 machining condition, better surface finish was obtained for the finished part because of the better chip breakability and less accumulation of chips near the cutting zone, and thereby, frictional contact of the chips with the finished workpiece are avoided. The surface finish was improved by 4–52% in CO_2 machining when compared to wet machining.

Comparison of Chip Forms

The chip shape and size are the major factors in chip breakability [18]. According to Kaldor et al. [19], there are two groups of chips, namely, acceptable and unacceptable chips. The acceptable chips do not create any hindrance to the machining work whereas the unacceptable chips cause a lot of problems including the disposal of chips as well as accumulation at the tool tips that sometimes causes the tool tip to break. The use of conventional coolant produced unacceptable chips, and the coolant jet was not effective in the removal of metal chips produced, whereas in CO_2 machining, the high pressure CO_2 jet helped the chips to break easily and to get removed effectively away from the cutting zone. The images of the chips obtained in dry, wet, and CO_2 machining environments are shown in Table 3.

In dry and wet machining, when the cutting velocity was 41 m/min, long thick tubular chips were produced and were hard to break as they were closely curled. Short tubular and fairly fine thin chips were produced in CO_2 machining. The chip breakability was good in CO_2 machining when compared with wet and dry machining as the chip changed into brittle nature on effective reduction in the cutting temperature at the cutting zone due to the better penetration of CO_2 coolant. As the feed rate was increased, the washer type chip which was curly in nature was obtained with the increased thickness in the case of dry and wet machining. At the cutting velocity of 94 m/min, the long snarled or ribbon type of chips were obtained in dry and wet machining. At this cutting velocity, when the feed rate was 0.051 mm/rev, short ribbon chips which are favorable for metal cutting operation, were obtained in CO_2 machining. On the increase of the cutting speed, the chip thickness obviously got thinner and had better chip breakability in the case of CO_2 machining. At high cutting speed of 145 m/min, short fine chips were obtained during CO_2 machining, whereas very long and snarled tubular chips were obtained in the case of dry and wet machining. Considerable increase in the chip thickness was witnessed whenever the feed rate was increased leaving the better chip breakability every time in CO_2 machining condition. At high cutting velocities, mostly discontinuous chips were obtained in CO_2 machining, whereas in dry and wet machining, continuous chips were obtained which resulted in poor surface finish of the product and more tool wear.

Conclusion

The CO_2 was used as the cutting fluid and coolant for turning AISI 316 stainless steel to control the cutting temperature effectively and to reduce the cutting forces to an extent of 35 to 55%. This resulted in lesser amount of wear in the rake and flank region of the cutting tool, producing the better surface finish. CO_2 cooling will be more advantageous as far as the high cutting velocities and feed rates are concerned as it produces better chip breakability and acceptable form of chips. CO_2 is a potential alternative for other cryogenic coolants especially in industrial conditions if the environmental aspects are taken care of.

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